Broadband Constant Beamwidth Beamforming MEMS Acoustical Sensors

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Overview

- Research objectives
- Research perspective
- Typical geometries of acoustic transducers
- Beamforming and beamsteering
- MEMS-based acoustical ultrasonic sensor arrays
- The State-of-the-art
- Broadband beamforming microarrays
- Advantages of non-planar arrays
- Design challenges
- Proposed structures
- Target design specification
- Future research plans

Objectives of the Current Research

- To develop a MEMS-based non-planar acoustical sensor microarray to provide broadband constant beamwidth variable directional sensitivity
- Precisely, the research work will concentrate on:
  - Develop a mathematical model for beamforming using a MEMS-based non-planar acoustical sensor microarray
  - Especially ultrasonic sensors will be investigated
  - Determine non-planar geometry suitable for fabrication using state-of-the-art MEMS fabrication techniques
  - Determine sensor type
  - Detailed sensor design
  - Optimize the performance matrix of the sensor
  - Behaviour simulation of the sensor geometry using 3-D finite element analysis method
- To develop a fabrication process to implement the non-planar sensor microarray
- Fabrication and testing of the microarray

Research Perspective

- Ultrasonic sensors have wide-scale applications, such as:

Underwater:

- Underwater imaging using ultrasound has been going on since WWI
- Sonar is used by scientists to map changes in the ocean floor
- Sonar is used by the military to detect and classify underwater objects
- Sonar is used commercially to protect ships from underwater hazards and to survey for oil and gas deposits.
- Currently Volumetric Sonar is a rapidly developing field

Research Perspective

Land Based:

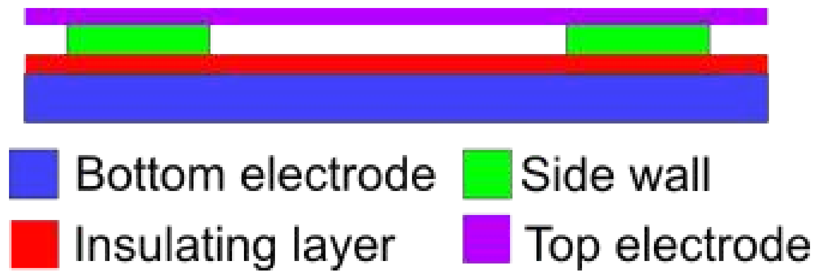
- Automotive Collision avoidance systems
- Machine Vision
- Industrial Safety Equipment
- Automated Industrial Quality Assurance

Bio-Medical:

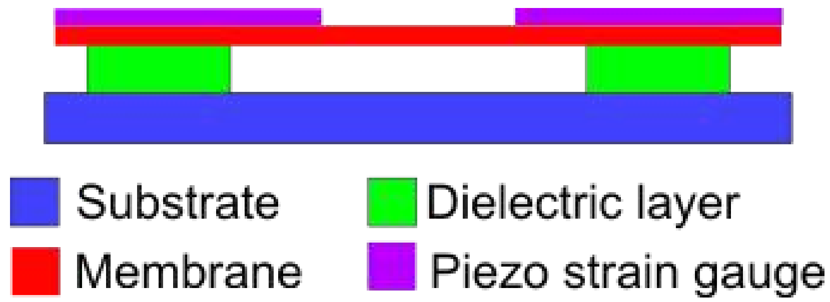
- Non-invasive imagining
- Guided biopsies
- Soft tissue therapy
- Extracorporeal shock wave lithotripsy

Typical Geometry of MEMS Ultrasonic Transducers

- Capacitive transducers require a bias voltage.
- Acoustical energy causes the diaphragm to move, resulting in a measurable capacitance change



- Piezoresistive transducers exploit the peizo properties of silicon or quartz
- application of an acoustic wave will strain the diaphram creating a measurable change in resistance



Typical Geometry of MEMS Ultrasonic Transducers

- Other transduction methods used in acoustic sensors include:
  - Resonant Pressure
  - Moving Gate FET
  - Optical

- MEMS acoustical sensors offer excellent performance characteristics
- In order to attain directional selectivity more then one sensor must be used to form an array.
- Arrays have the benefit of being configurable for beamsteering and beamforming operations[1]

Dynamic Range of Capacitive MEMS Ultrasonic Transducers (cMUTs)		
	Current	Limit
Air cMUTS	110 dB	130 dB
Immersion cMUTS	60 dB	130 dB

cMUTs Sensor size	
Length (µm)	6000
Width (µm)	200
Elements / Cell	750
Cell Radius (µm)	36

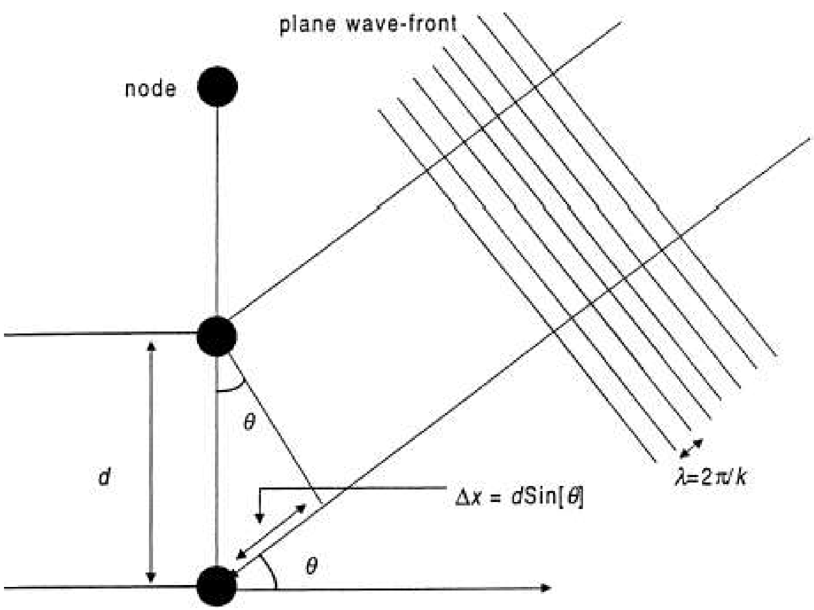
Beamforming

Beamforming is another name for spatial filtering where an array of sensors together with appropriate signal processing can either direct or block the radiation or the reception of signals in specified directions.

- John A. Stine -

- The array factor is used to illustrate the effects of element position and weighting on the radiation pattern:
- The signal must travel a distance that varies as shown in the figure
- General data independent beamforming is based on a fixed size array
- it attempts to achieve a specified performance by applying frequency response sampling and linear weighted least squares [4]

$$AF(\theta) = \sum_{n=0}^{N-1} w_n e^{jn\left(\frac{w}{c} d \cos\theta\right)}$$

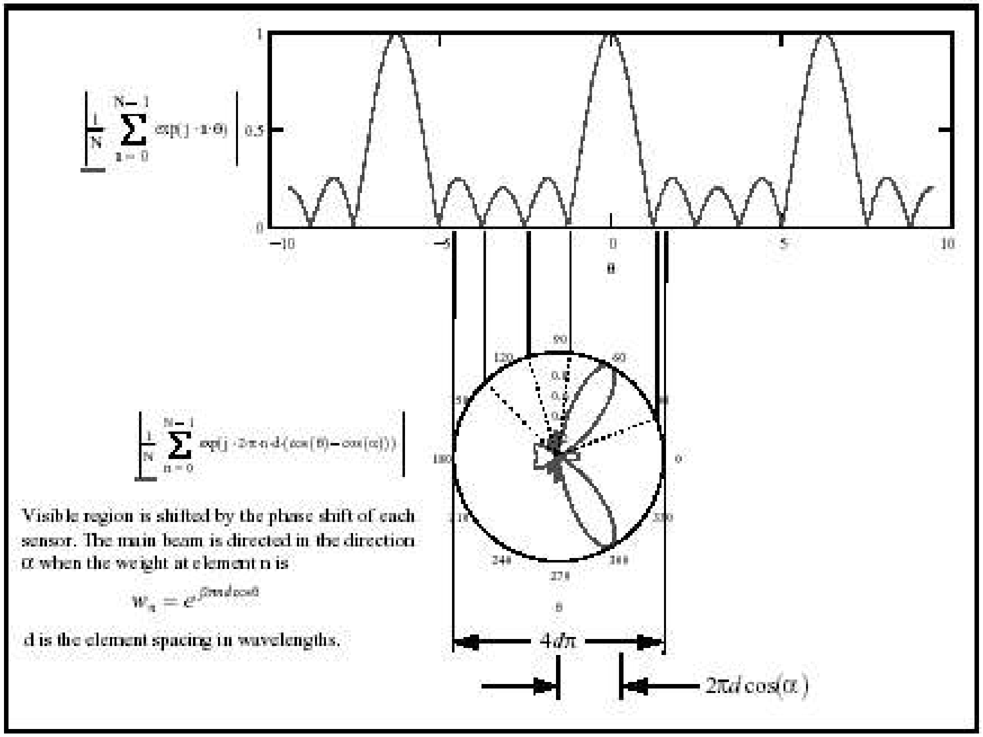


Beamsteering

Beam steering is the technique of directing an antenna s main beam in a specified direction by weighting each sensor[in the array]

- John A. Stine -

- In beamsteering, the weighting of each sensor is related to the propagation time to achieve a linear phase characteristic in the desired direction
- Many algorithms exist for determining the sensor element weightings.
- Fixed weighting systems exist as well as adaptive algorithms [4]



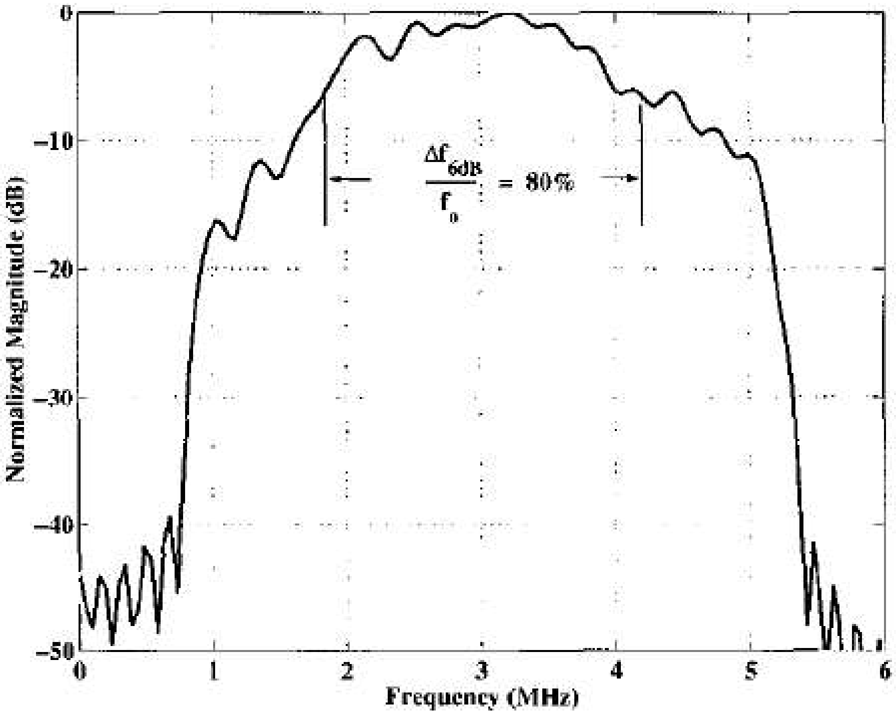
MEMS-based Acoustical Ultrasonic Sensor Arrays

- Because of the importance of Ultrasound technologies, this field continues to see growth and development
- Beam-forming transducers are a critical requirement for improving ultrasound based systems performance
- High element count linear arrays (128 x 128 and higher) are commonly used to help improve resolution
- Because MEMS diaphragms are very thin (typically < 1μm), they are very sensitive to low power signals.
- Because MEMS microarrays are fabricated on the same wafer, all elements are very tightly matched for sensitivity, eliminating one of the difficulties with macro scale arrays
- Arrays can be fabricated with excellent spacing accuracy since all elements are fabricated on a single die

The State-of-the-Art: MEMS Transducers

- Capacitive MEMS Ultrasonic Transducers
- Current product line includes MEMS:
  - 192 Element linear 9Mhz arrays
  - 128 Element curvilinear 4MHz convex arrays

Curvilinear cMUTs array before mounting



cMUTs 128 Element 1D Linear Array Response

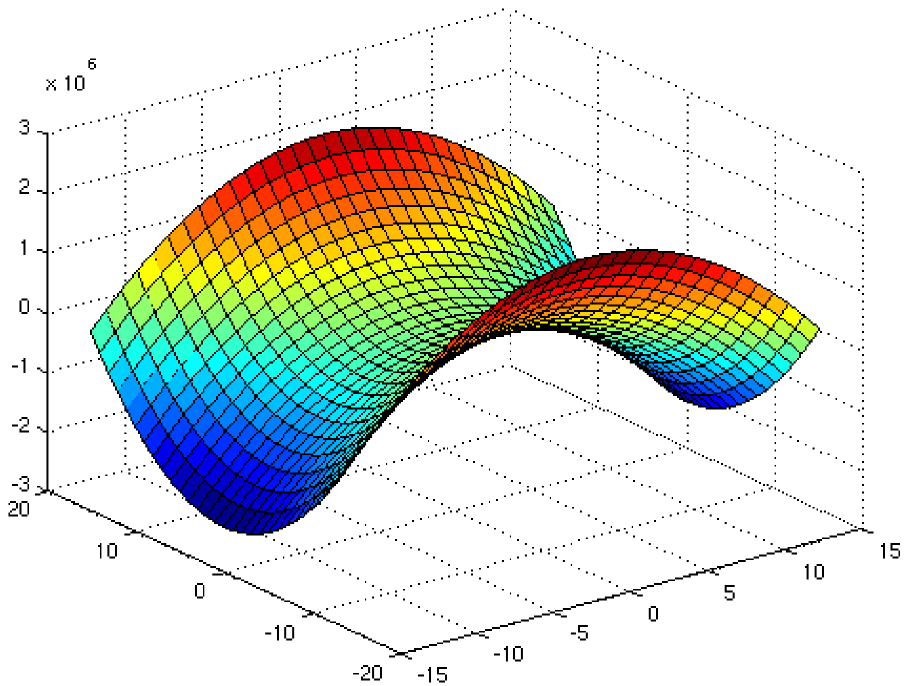
Images Courtesy www.sensant.com

Beamforming Broadband Transducers

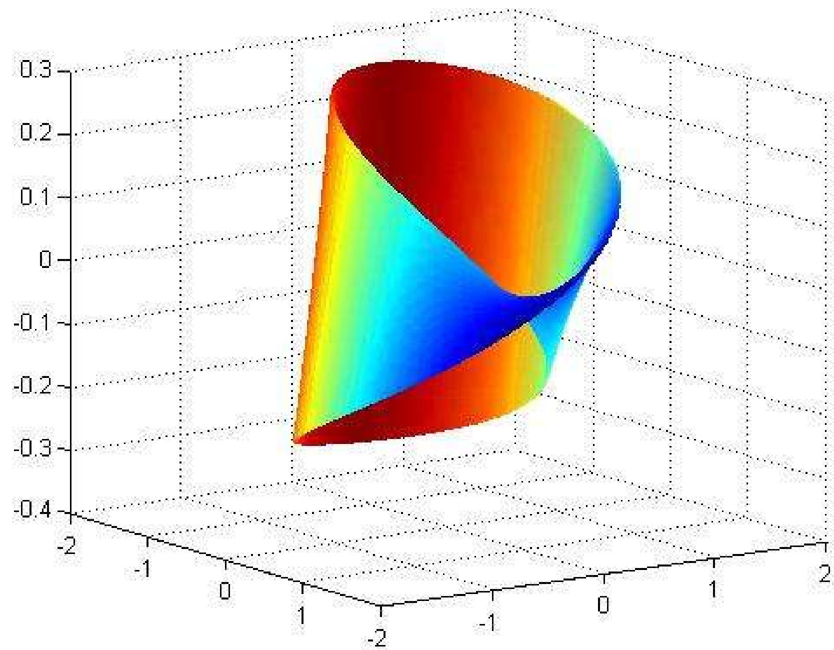
- Conventional planar arrays of fixed size have beam-widths which decrease as the frequency rises and therefore cannot be used in a broadband system
- Planar arrays can have relatively constant beam-widths over a frequency range ratio of 9 – 10 by using delay lines, filters, DSP and other techniques
- One approach to the problem of 2-D beamforming is to use a pair of planar transducers with constant beam widths in one direction, and wide beam widths in the other direction. In applications where this isn't desirable, a transducer with a constant beam width in 2 directions is needed
- An alternative approach to is to create a non-planar transducer array which allows the natural propagation delay to replace the delay lines, reducing the complexity of the required circuitry dramatically and removing the maximum frequency ratio [3]

Beamforming Broadband Transducers

- At least two geometries will yield an approximately constant 2D broadband beamforming array [3]
- The geometries under study are:
  - Hyperbolic paraboloid
  - Linear twist



A Hyperbolic Paraboloid



A Linear Twist

Mathematical Model for Beamforming Using a Hyperbolic Paraboloid Geometry

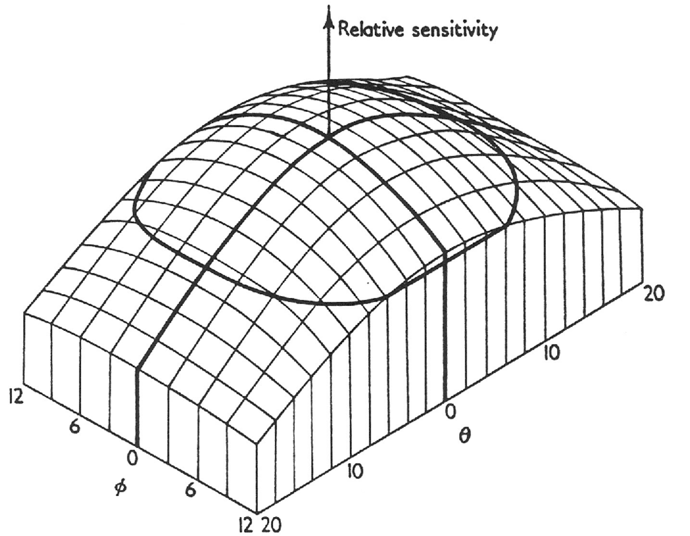
- Morris outlines two lines of reasoning from which these geometries are derived [3]:
  - Ray Theory
  - Synthesis Theory
- For small angular twists both of these geometries have the same governing equation for sensitivity

$$f(\theta,\phi) = \frac{1}{LY}\int_{-L/2}^{L/2}\int_{-Y/2}^{Y/2} e^{j2\pi n\left(x\tan\theta + y\tan\theta + \frac{xy\alpha_2}{L}\right)}dxdy$$

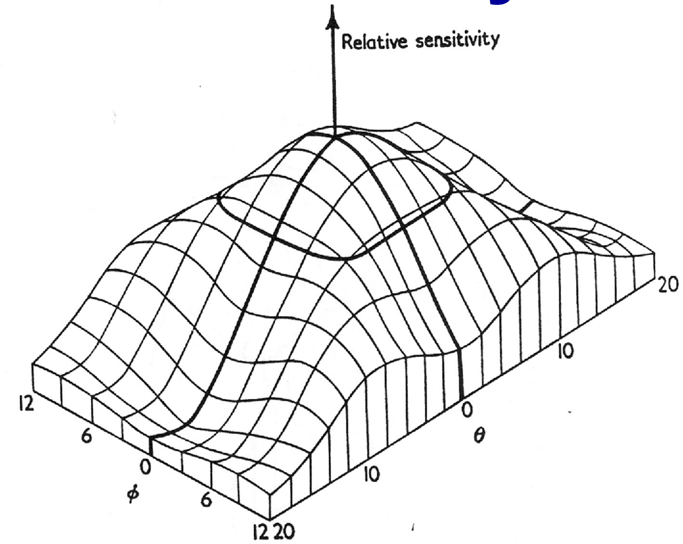
$$n = \frac{1}{\sqrt{\tan^2\theta + \tan^2\phi + 1}}$$

L – Length in wavelengths along x-axis
Y – Length in wavelengths along y-axis
α_2 – Angle the array extremity makes with the axis (matched x & y)
θ – Angle made with nominal array normal in x direction
ϕ – Angle made with nominal array normal in y direction

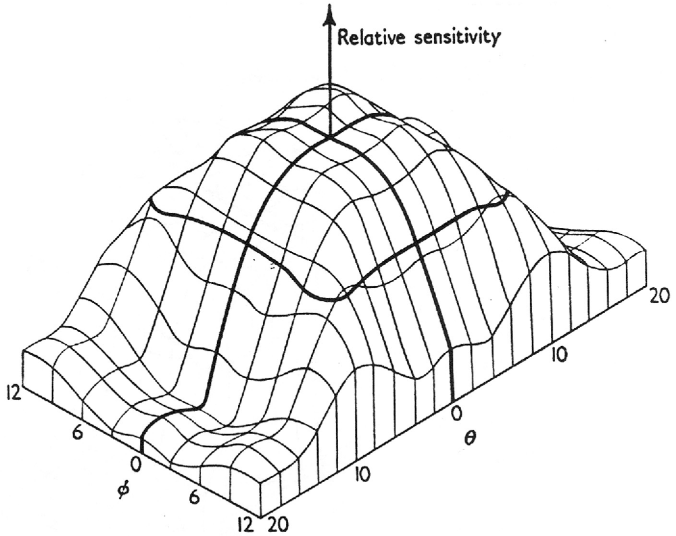
Beamwidth and Sensitivity of a Hyperbolic Paraboloid Geometry



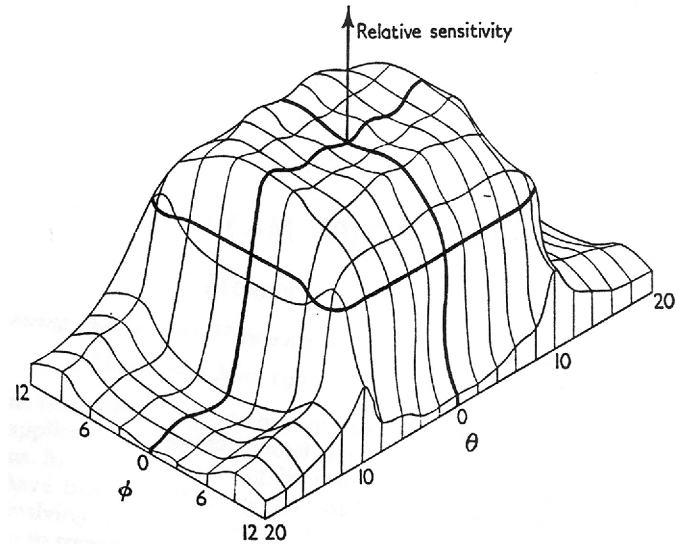
2λ x 2λ Array



5λ x 5λ Array



8λ x 8λ Array



20λ x 20λ Array

Images Courtesy of [3]

Observations

- When the array size is below that of a conventional array the beam width increases as expected
- Beam pattern shrinks from 2λ to 5 λ
- Beam pattern returns to designated size by 10λ and remains unchanged for all higher frequencies
- As frequency increases beyond 10λ, the response in the pass region continues to flatten out, this will manifest as reduced ripple in the pass region

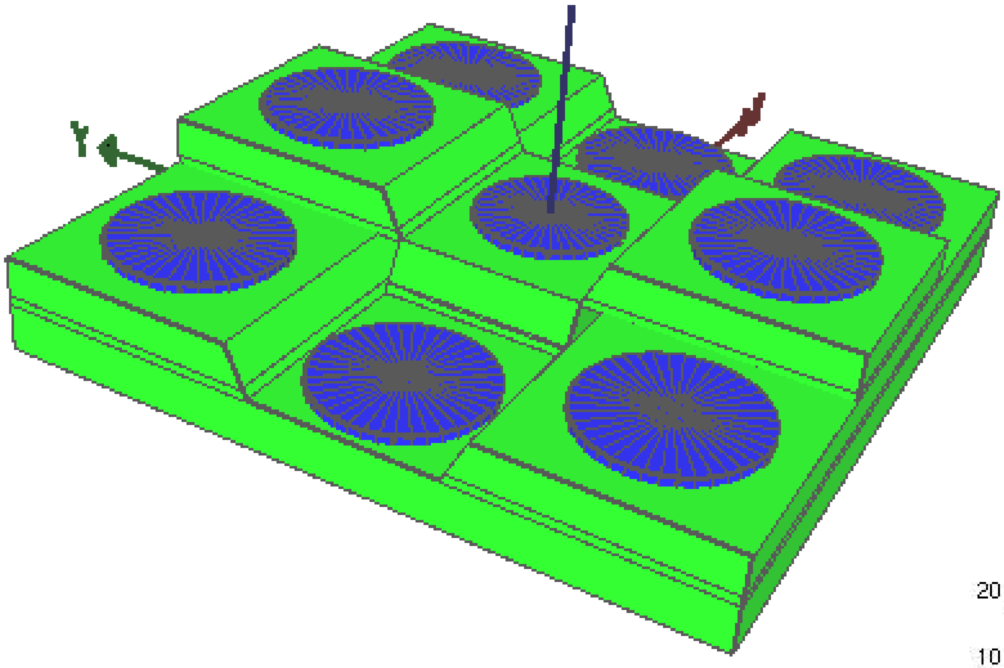
Advantages of Non-planar Geometries

- Elimination of electrical delay lines and associated circuitry
- Simpler design
- Reduced die size
- Reduced fabrication cost
- Lower noise
- Lower power requirements
- Better signal integrity
- Truly “broadband” – maximum frequency determined by signal processing equipment
- Beamforming in 2-D is provided by exploiting the specific array geometry

Design Challenges

- To develop an accurate mathematical system model for geometric approximations
- To adapt planar MEMS fabrication techniques to fabricate non-planar structures
- To devise a cost effective process to implement the design in terms of fabrication steps

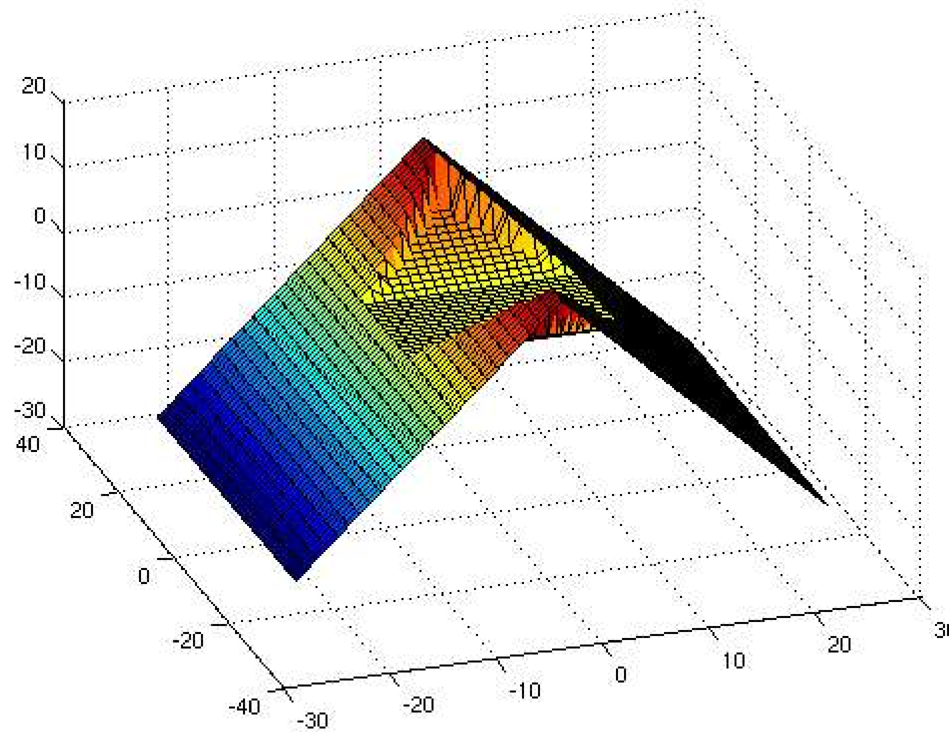
Proposed Structures



Sample of a tiered layout

Additional tiers can be incorporated, such as 5, 7, 9, etc. elements per axis

Sample of a pyramidal layout



Preliminary Target Design Specifications

- 110 dB dynamic range
- 9-21 elements per axis
- 7 mm x 7 mm sensor area
- 10 ° – 30° beam width
- 3V (maximum) drive voltage
  (compatible with standard CMOS drive levels)
- Fabrication by batch compatible methods

Future Research Plan

- Investigate twisted array geometries
- Develop a mathematical model for tiered MEMS microarrays
- Determine sensor type
- Determine element count
- Detailed design and verification with 3D finite element analysis methods
- Develop a fabrication process compatible with state-of-the-art MEMS fabrication techniques
- Fabrication and verification against theoretical and FEA results

References

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